Multiphoton Optics®

a company of Heidelberg Instruments

Introduction to Multiphoton Lithography and selected Application

GenISys BEAMeeting 2022

Dr. Jonas Wiedenmann

Head of Application Engineering

29/03/2022

Multiphoton Lithography
Real 3D printing with micro/nano resolution on arbitrary substrates

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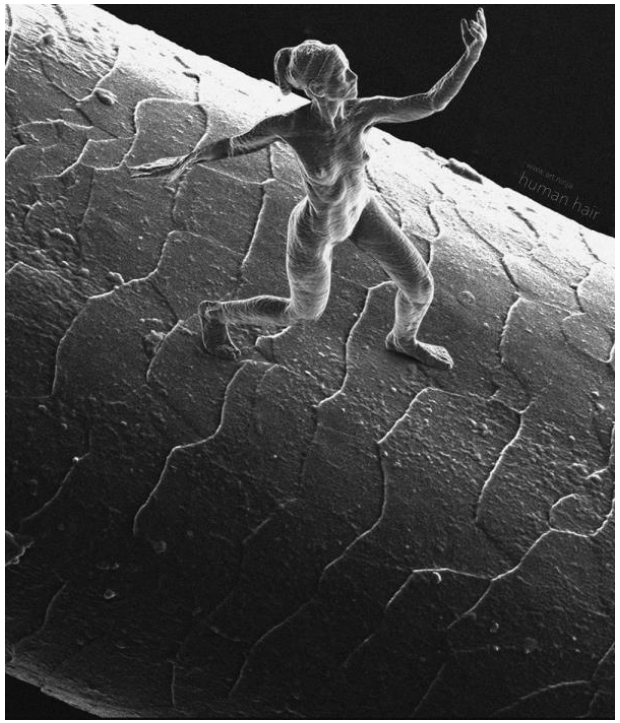

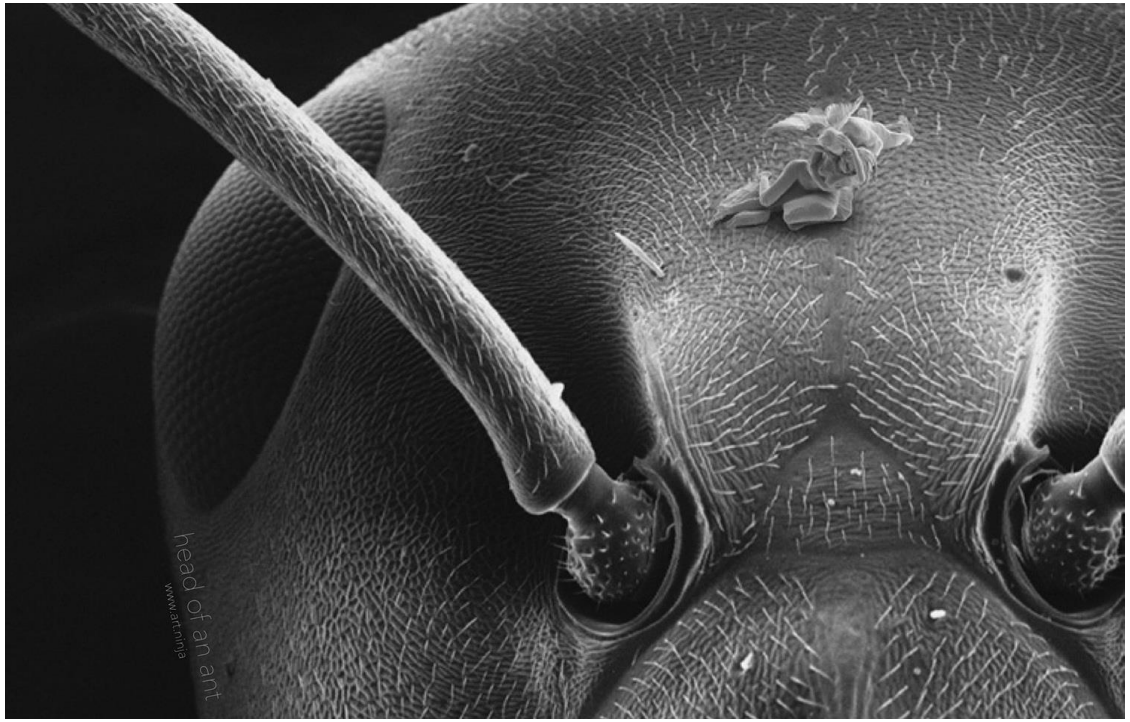

TRUST
Sculpture printed on human hair
80 x 100 x 20 microns

CUPID AND PSYCHE
The Second Kiss
10 x 9 x 10 microns

Nano Sculptures by Jonty Hurwitz — The Art of Jonty Hurwitz

Basic working principle:

Two photon absorption a nonlinear optical effect

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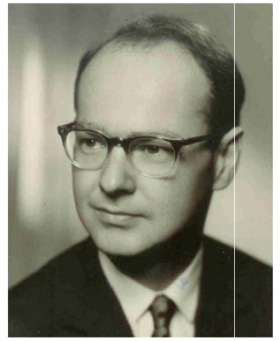
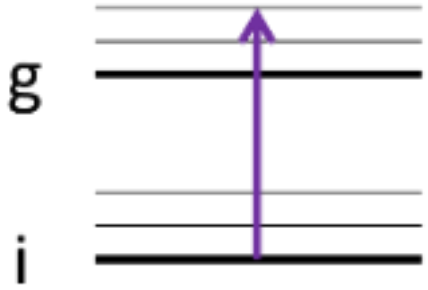
1930: Marie Goeppert Mayer
→ Theory on Two-Photon-Absorption

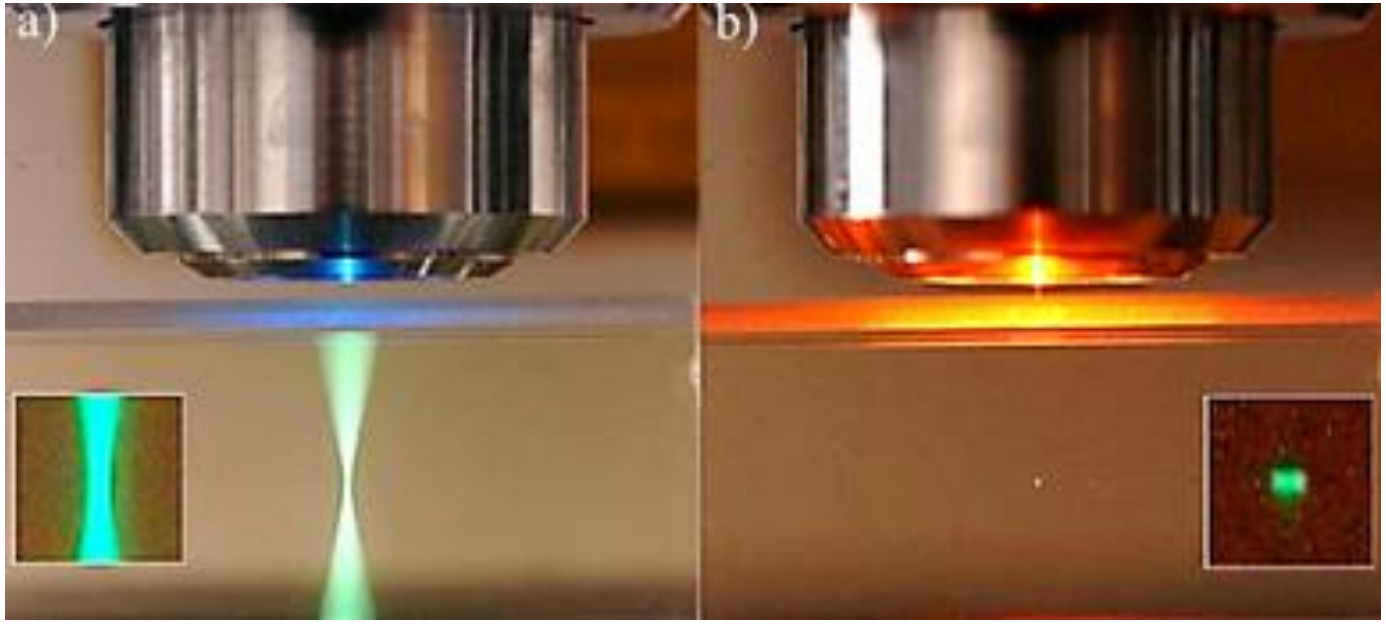
1960: First experiments on two-photon absorption by W. Kaiser and C. Garett at Bell labs
(required invention of lasers)



1 Photon Absorption



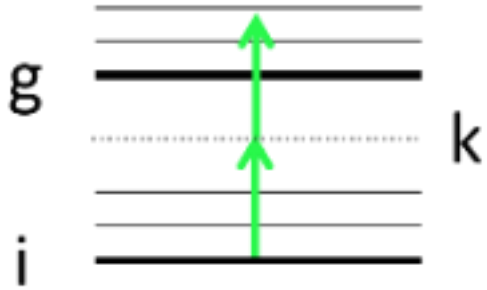
Absorption of **one** photon from ground state to excited state.



Fluorescence (absorption) along the whole beam path.

transparent in the NIR regime.
Two photon absorption occurs only the focal point

2 Photon Absorption



Simultaneous absorption of **two** photons (virtual state)

Image by Steve Ruzin and Holly Aaron, UC Berkeley

Core Technology: Two-Photon-Polymerization (TPP)

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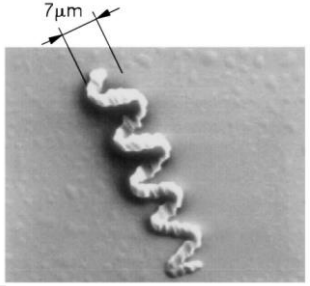
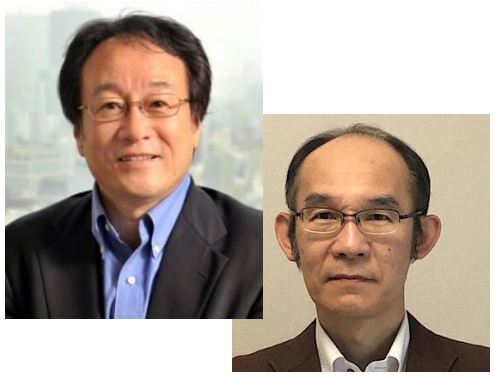
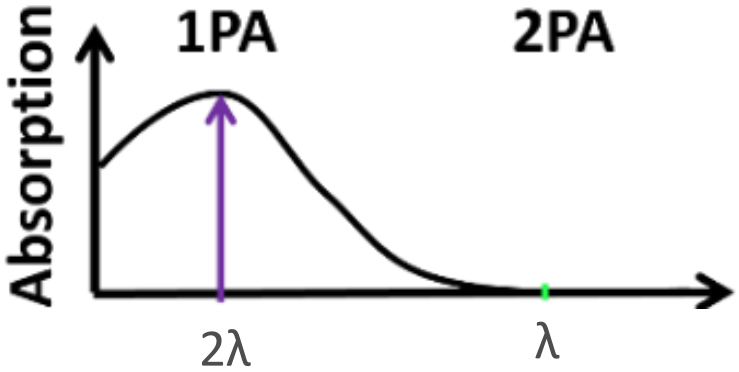
1997: First experiments on two-photon laser lithography (TPP) by S. Maruo and S. Kawata, Opt. Lett. 22, 132

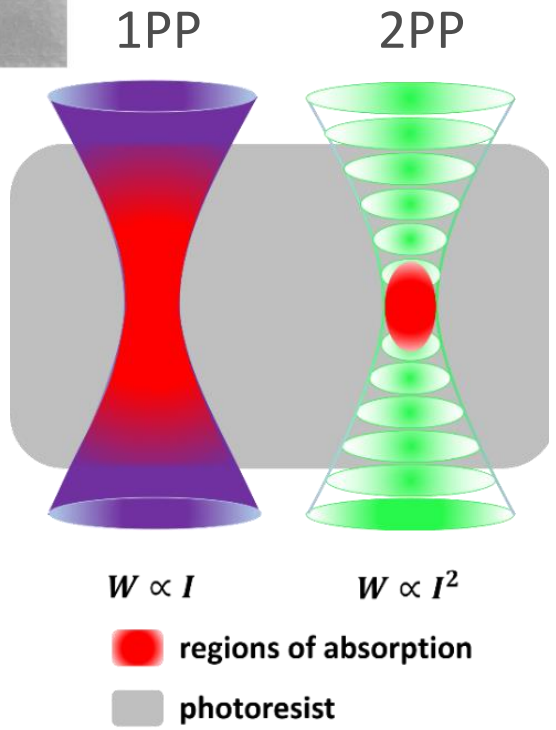




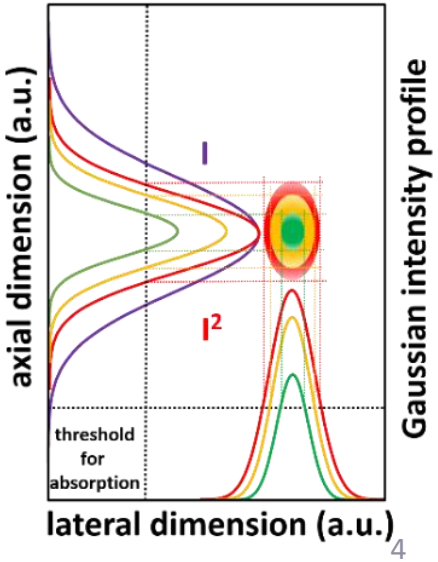


The photoresist is transparent for the fundamental wavelength of λ but absorbs light at 2λ.

Mechanism of TPP
TPP is a photochemical process initiated by focusing light into the volume of the photosensitive resins. Polymerization occurs by the simulationeous absorption of two photons.



Beyond an intensity level (threshold value) locally confined polymerization is triggered.
The smallest building block is called a voxel (volume pixel).



Core Technology: Direct Laser Writing (DLW)

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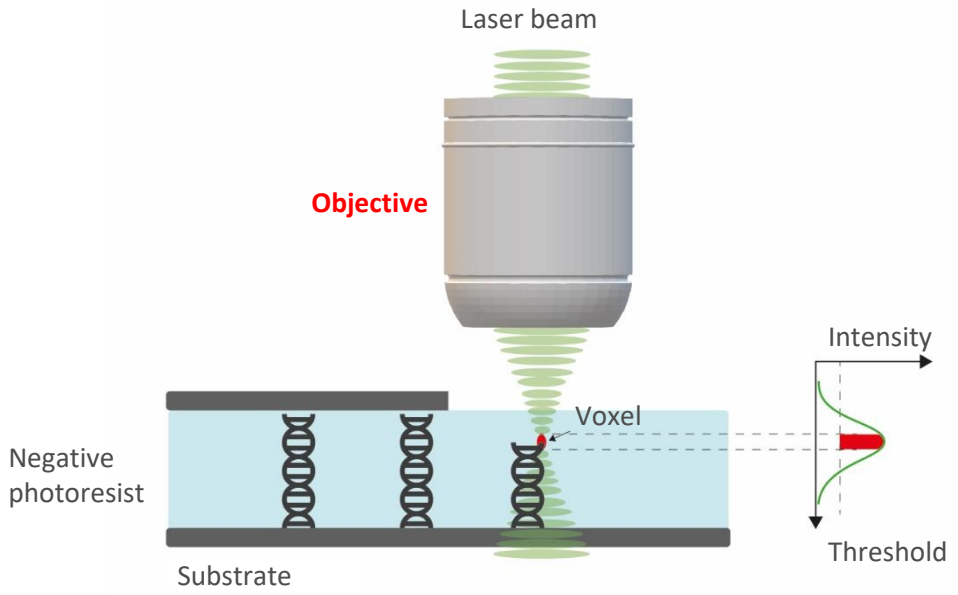
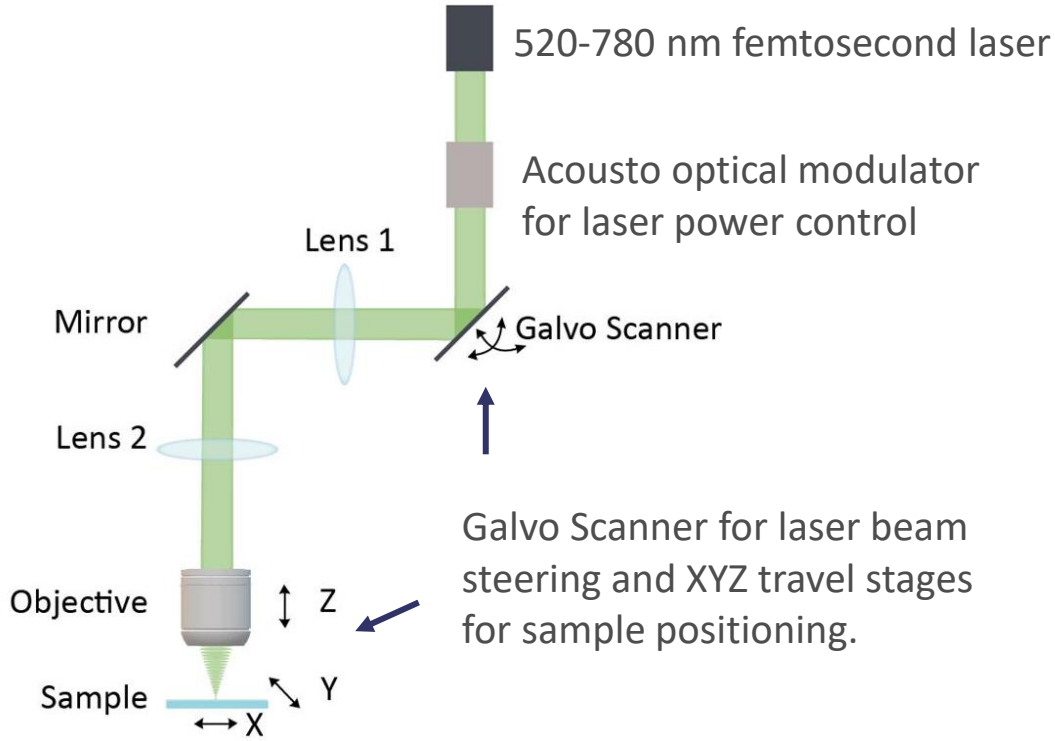


laser moving through the volume of the photoresist along all three spatial dimensions. **Complex 3D structures are written along the laser's trajectory (Analogy: paint brush).**

A typical two direct laser writing setup.



Galvo Scanner for laser beam steering and XYZ travel stages for sample positioning.

Resolution and Feature Size

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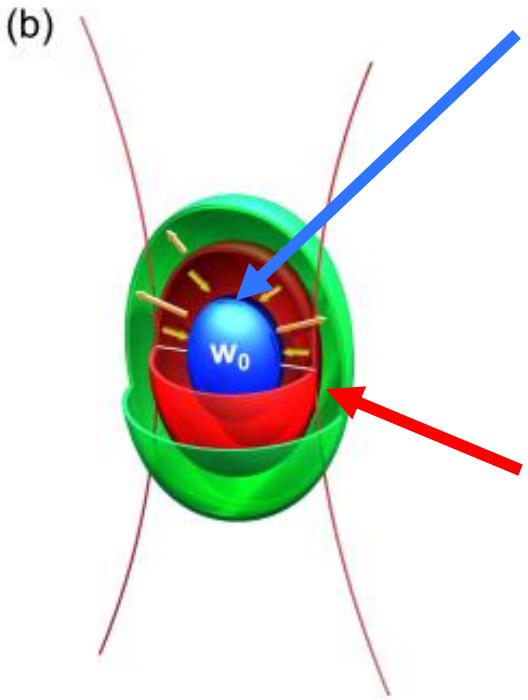


Polymerization threshold:

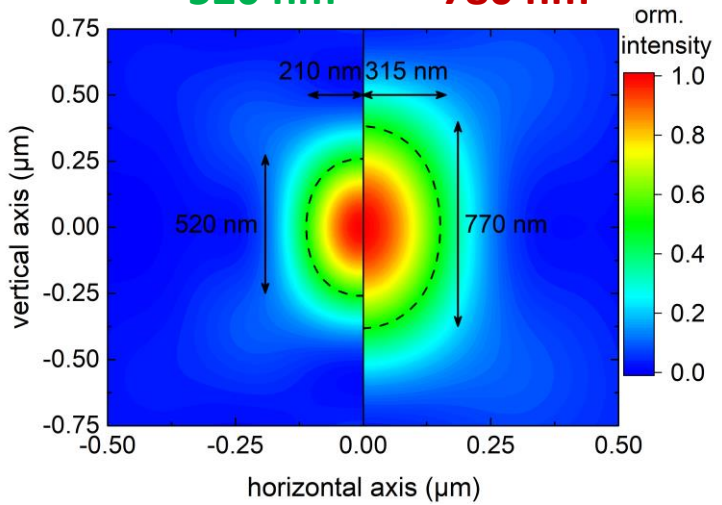
- Number of 2PP induced free radicals must be **larger** than a threshold.
- Inhibition effects need to be overcome (e.g. O_2 quenching, Schwarzschild effect)
- In theory arbitrarily small voxels possible!

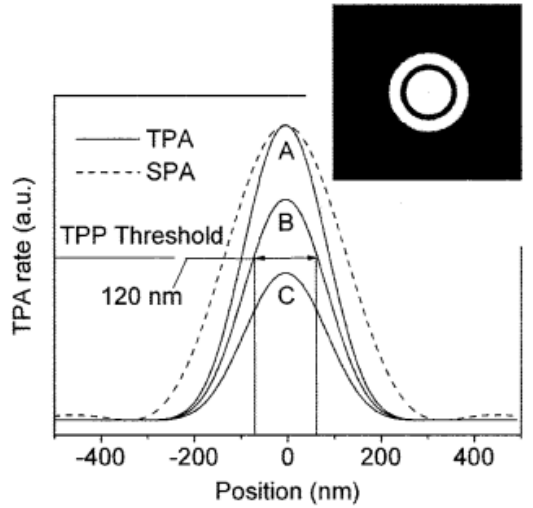
Technical volume

- Optics (∝ 1/numerical aperture NA)
- ∝ Wavelength
- **Nonlinearity I^2**
- Spherical Abberations

PSF simulation

Immersion Na 1.4





Hong-Bo Sun 2003
Houbertz 2010

Resolution and Feature Size

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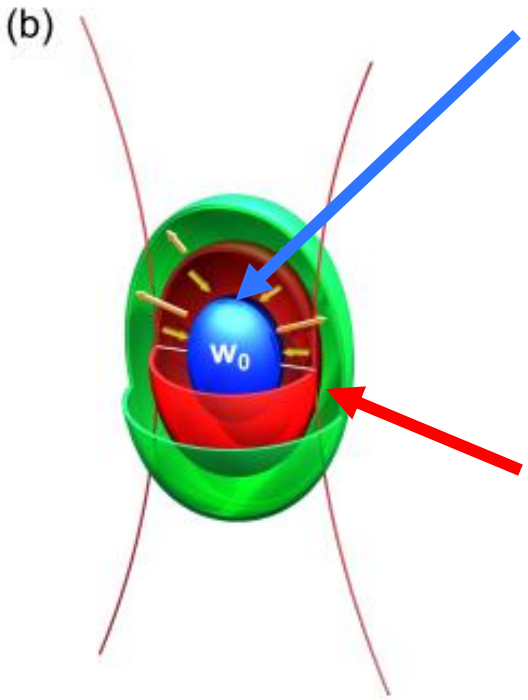

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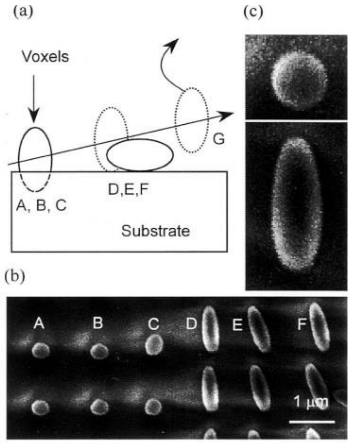
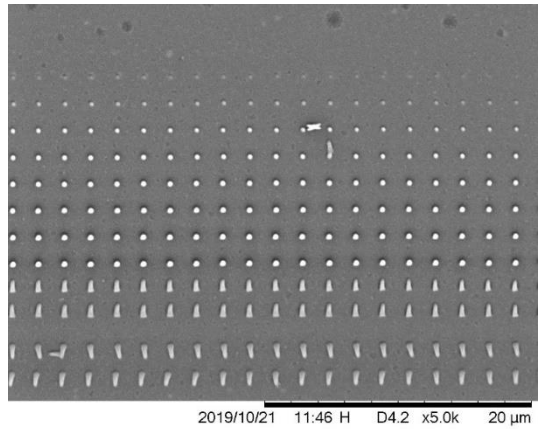
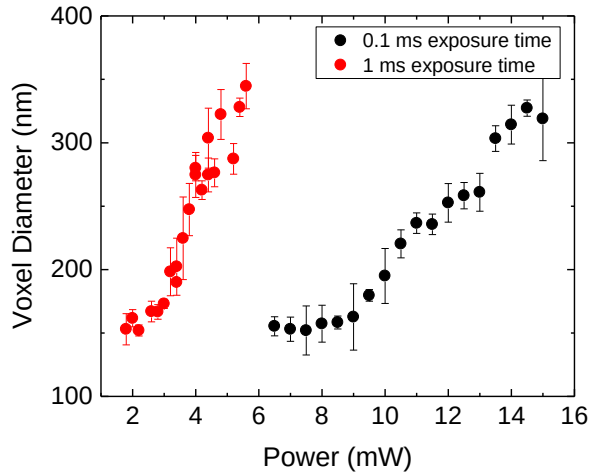
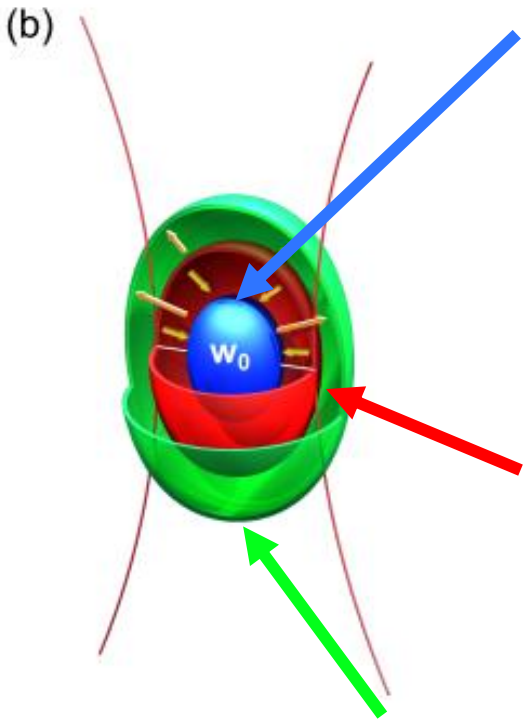






Hong-Bo Sun 2003
Houbertz 2010

Resolution and Feature Size



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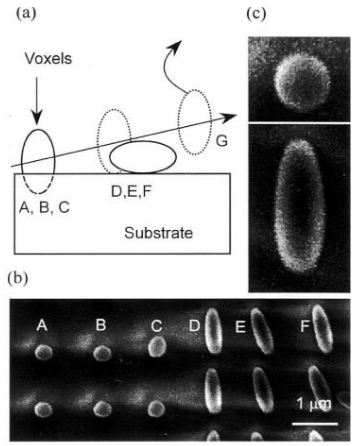
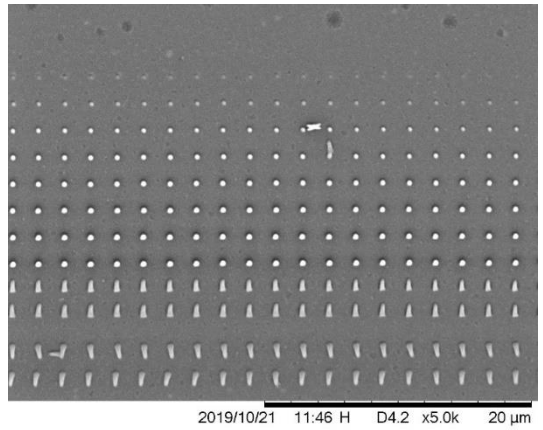
Chemical Volume

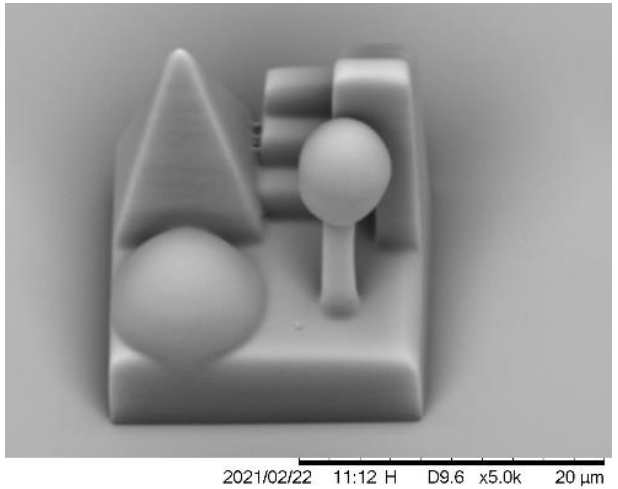
- Diffusion processes
- Reaction kinetics
- Size of monomers

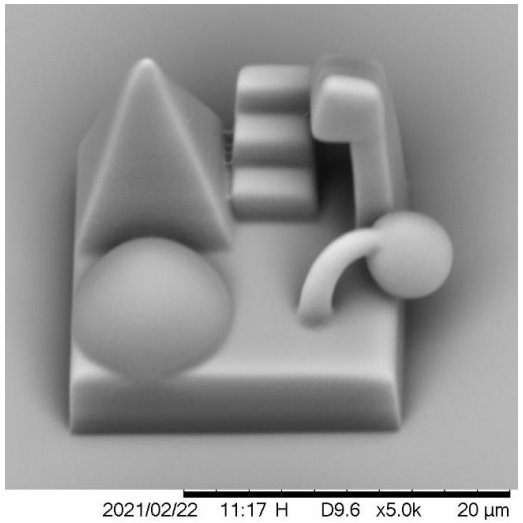
Material properties

- Degree of conversion, shrinkage, mechanical properties, refractive index…









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Resolution and Feature Size

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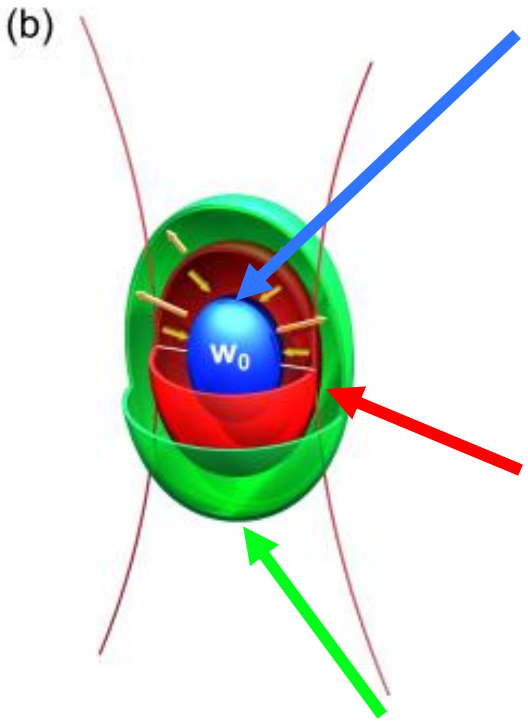

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Material properties

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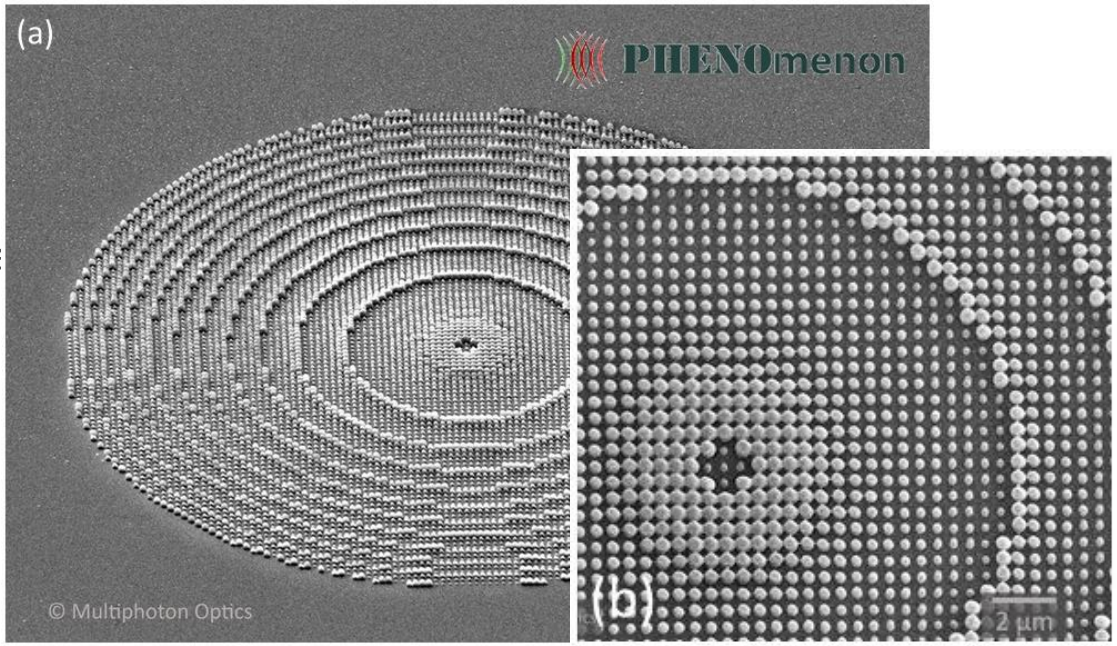
Houbertz 2010

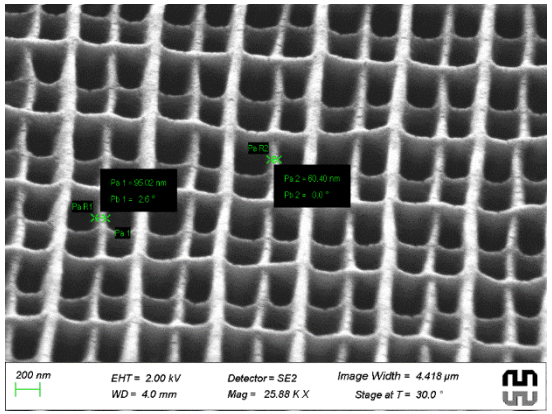
…100 nm feature size



… Push it to the limit

60 – 100 nm lines
@ 350 nm pitch

≠ Resolution!!



Submicrometer Processing: Scaling Pixel Size of DOE

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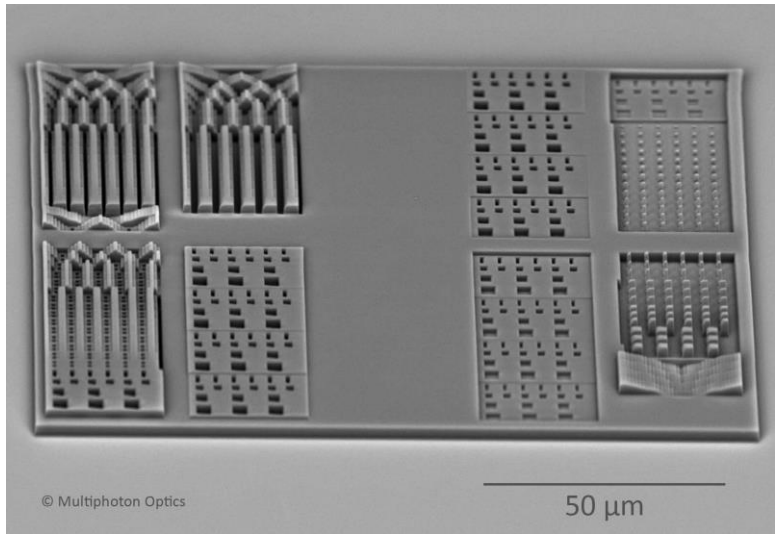
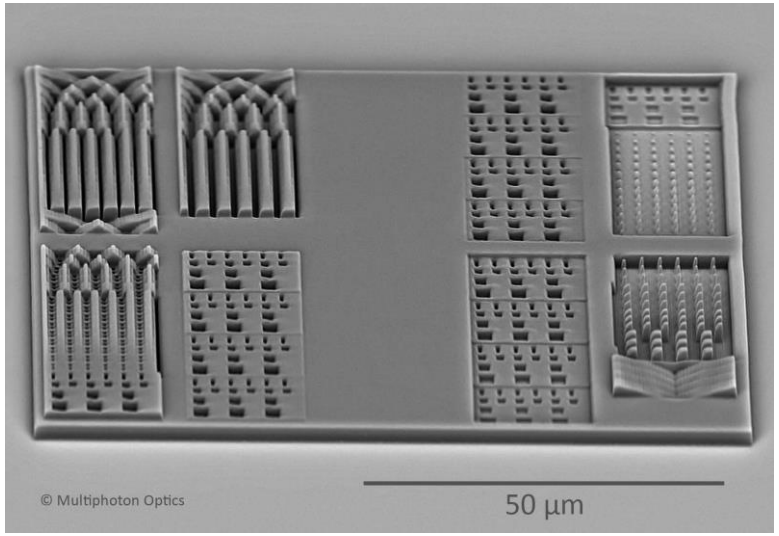
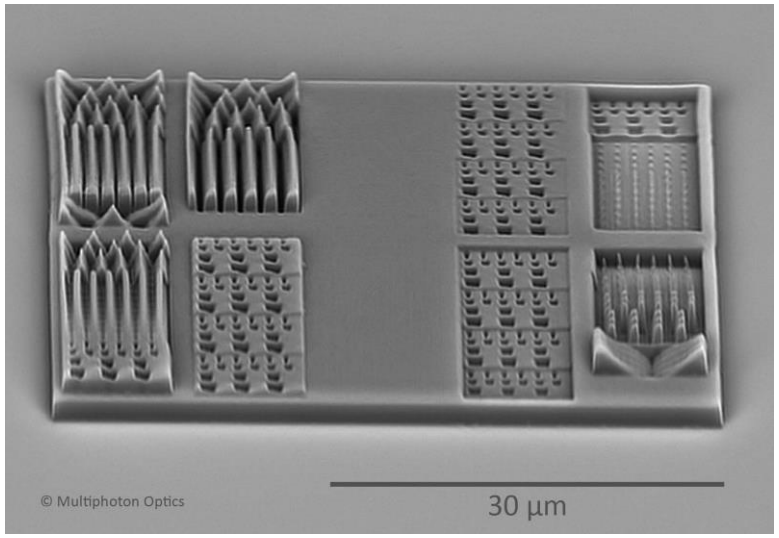
Inter-layer distance 200 nm, total height 4.8 µm



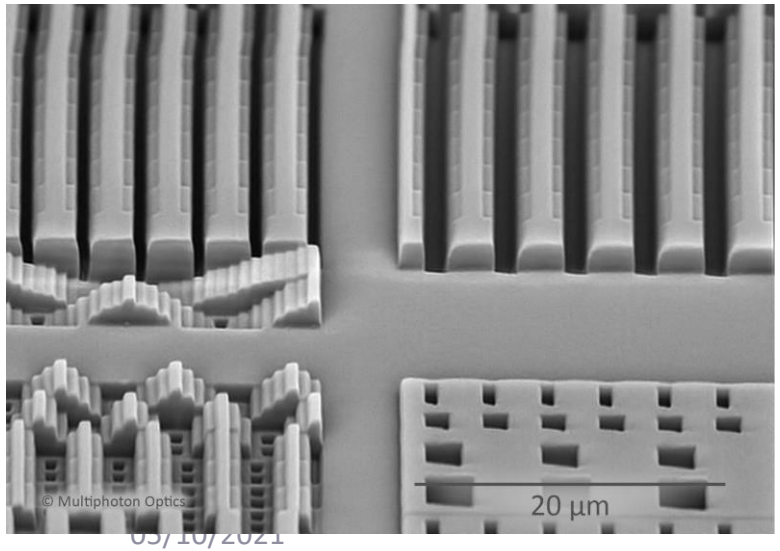
Pixel Size 750 nm

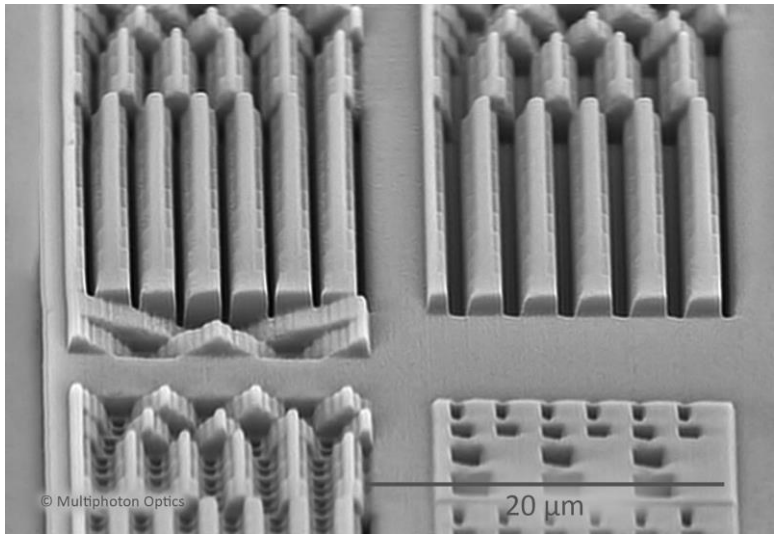


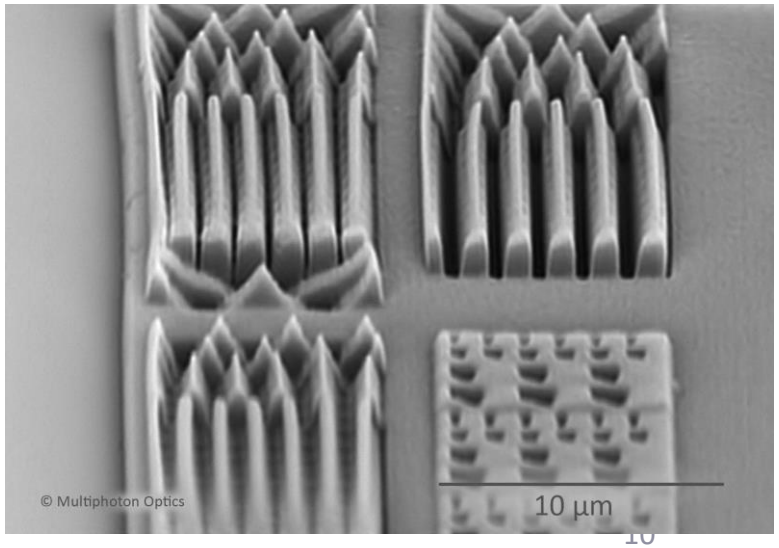
Pixel Size 500 nm



Pixel Size 250 nm







Two Photon Polymerization (TPP)

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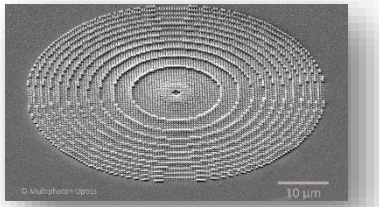
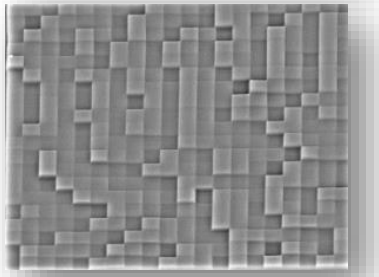
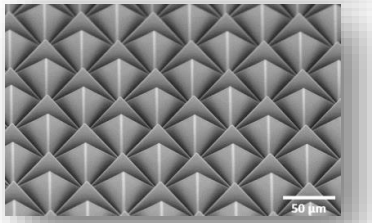
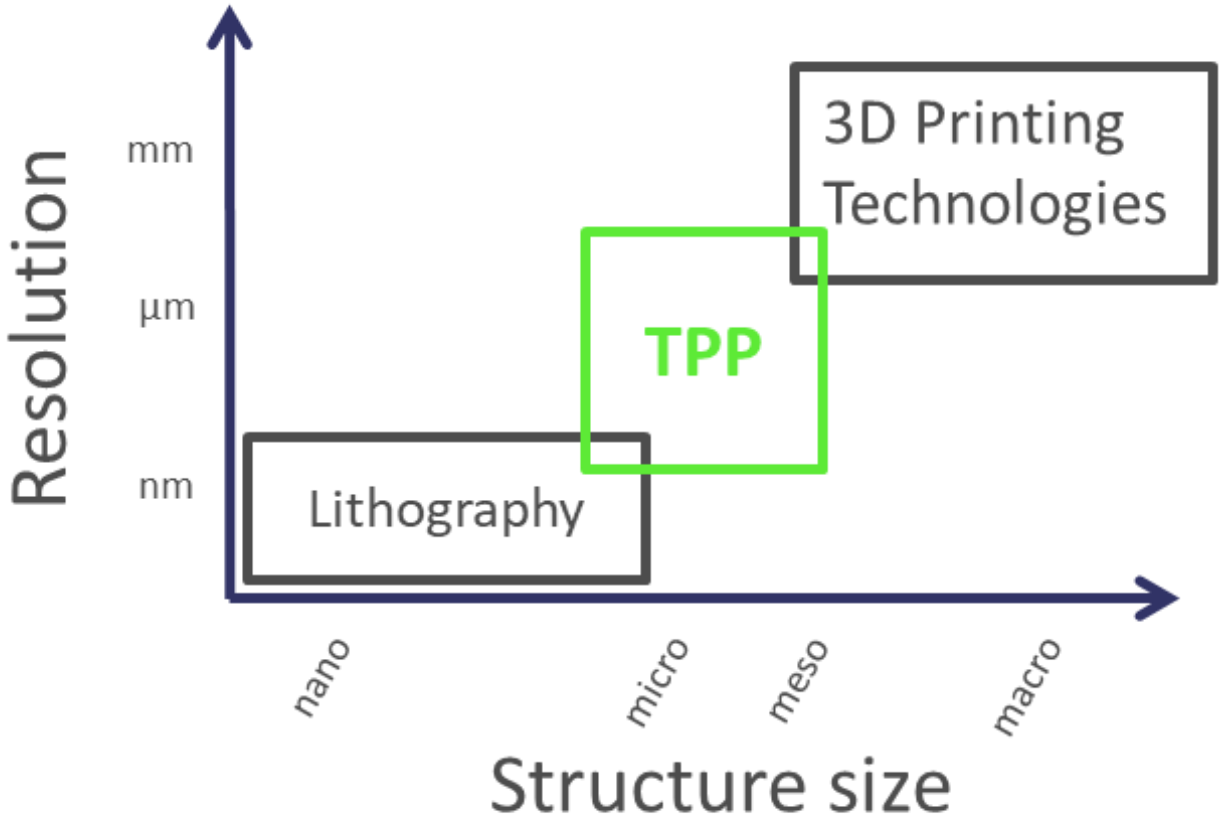
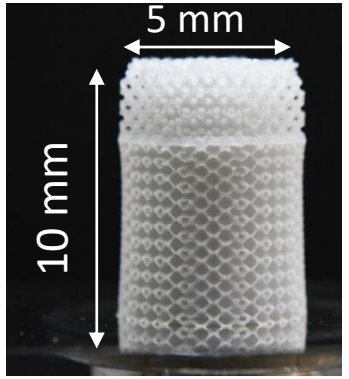
TPP for 3D lithography ⟵ **Bridging the Gap** ⟶ **TPP for micro 3D printing**

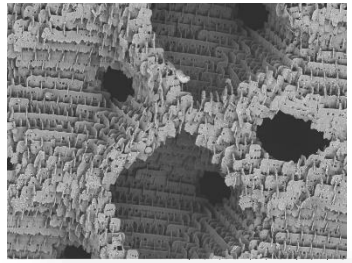


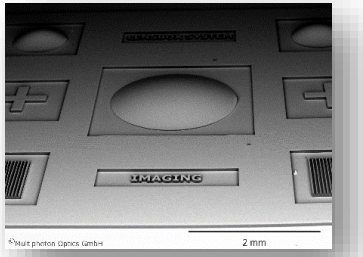








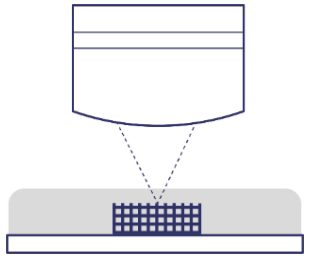




Resolution: < 1 µm
Structure height: < 1 mm

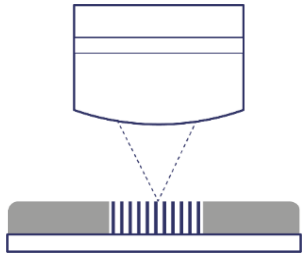
Resolution: 1 - 10 µm
Structure height: 1 - 25 mm

Material



Additive Fabrication

ORMOCER®s
SU-8
Ceramic compounds
Biodegradable resists
Hydrogels
Acrylates
…



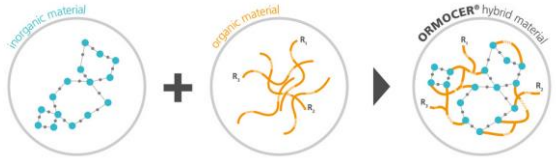
Subtractive Fabrication

AZ resist
ma-P 1200 resist
metal films(Ag, Au, Cr, …)
…

ORMOCER® - ORganically MOdified CERamic

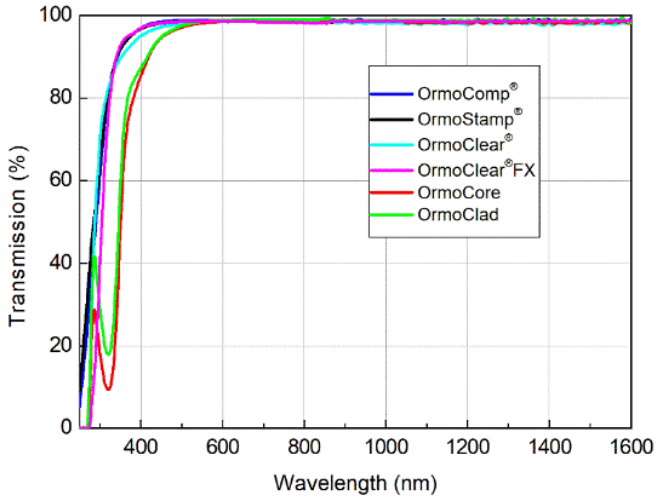
Hybrid polymer with organic and inorganic components

- High thermal and chemical stability
- Very high transmission
- Excellent mechanical properties
- Ideally applicable as functional component

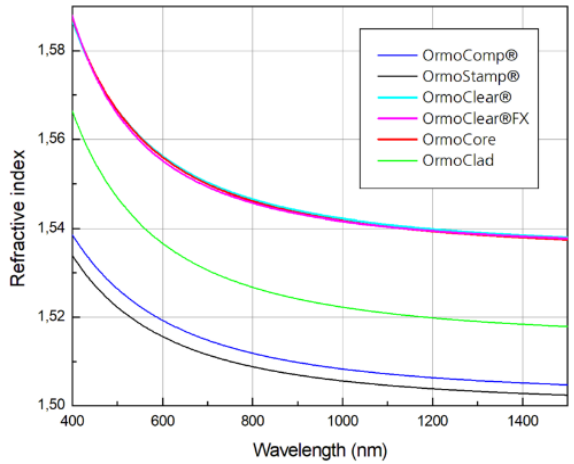


Fraunhofer micro resist technology

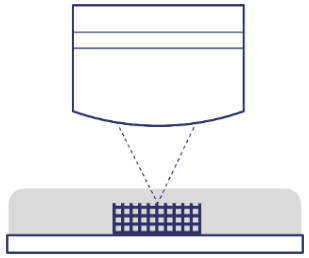
Transmission



Dispersion

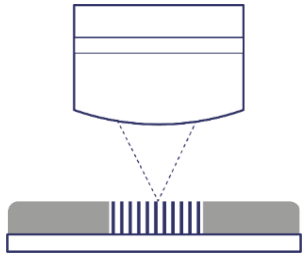


Material



Additive Fabrication

ORMOCER®s
SU-8
Ceramic compounds
Biodegradable resists
Hydrogels
Acrylates
…

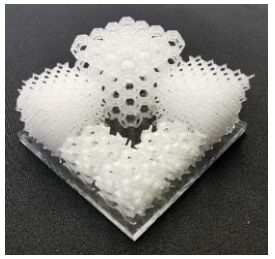


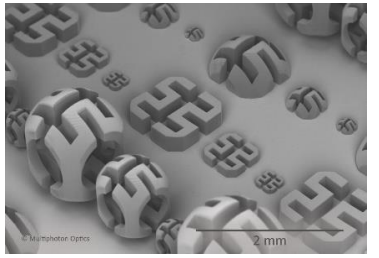
Subtractive Fabrication

AZ resist
ma-P 1200 resist
metal films(Ag, Au, Cr, …)
…

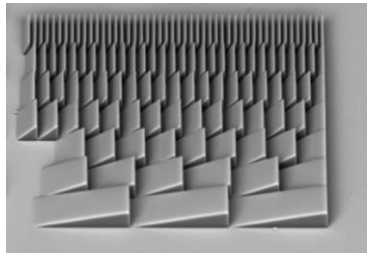
OrmoComp®

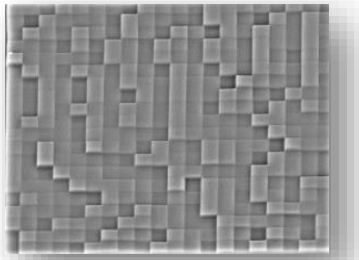
- Scalable (20 mm) and high-speed printing (> 1.5 m/s)



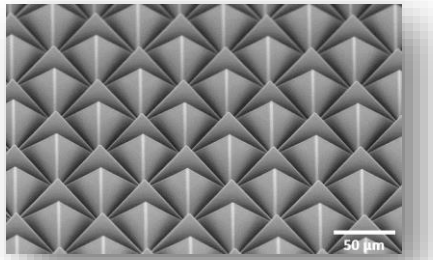


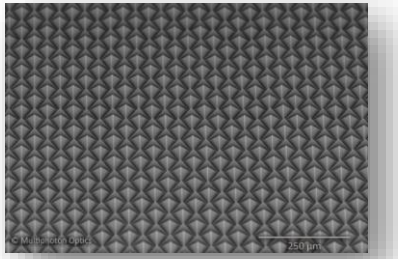
- High resolution & Optical grade surfaces (Ra < 10 nm)





- Master for molding





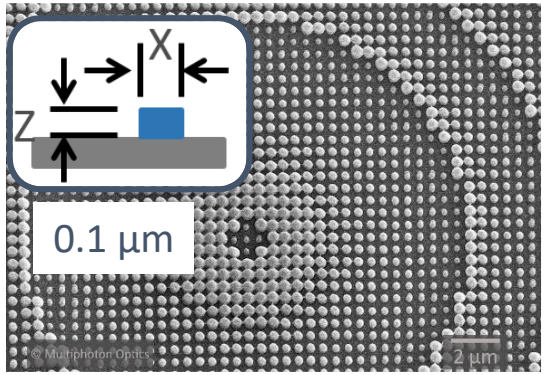
TPP Fabrication Process | Unparalleled design freedom

Multiphoton Optics®
a company of Heidelberg Instruments

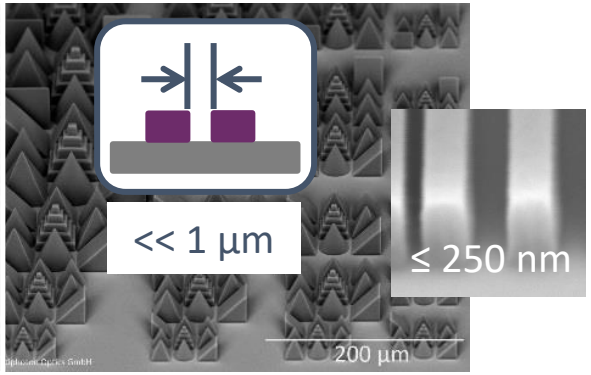
Nano – Micro – Meso – Macro

Multiphoton Optics' technology removes limitations in design and enables the creation of free-form 3D structures on virtually any substrate including active devices.

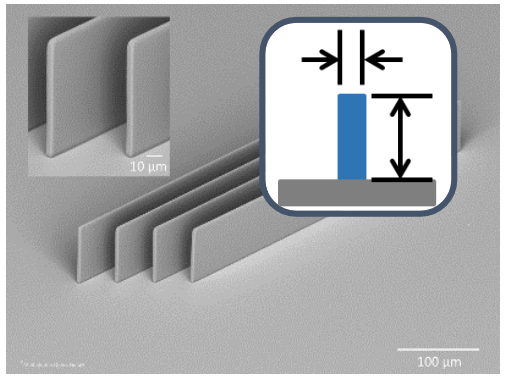
Features sizes can be as tiny as 0.1 µm



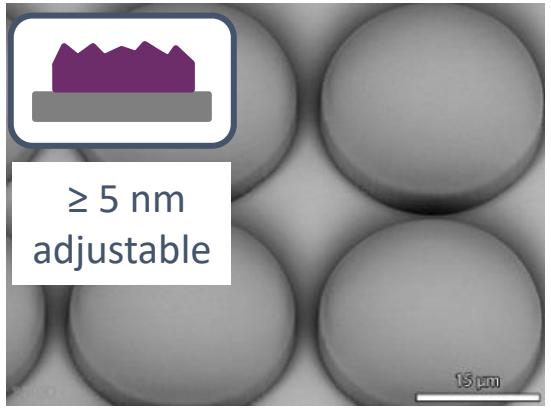
Objects can be much closer than 1 µm



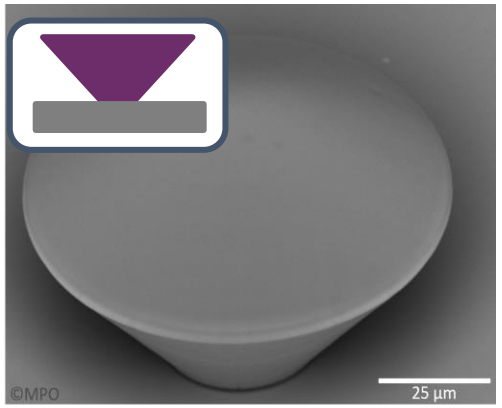
Extreme aspect ratios of 16:1 and above



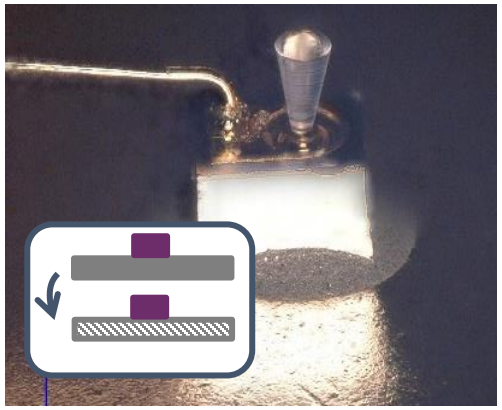
Achievable roughness can be adjusted as smooth as 5 nm



Overhangs do not require supporting

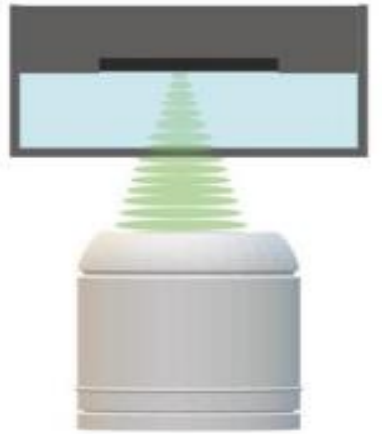


Substrate can be chosen independently



Exposure Setup

Multiphoton Optics®
a company of Heidelberg Instruments

	Immersion	Air	Dip In	Bath
exposing at the bottom (free choice of substrate)				
exposing at the top (transparent substrate)				

Resolution	+++ (++)	+(++)	++	+
Abberations	varying	varying	constant	constant
Structure height	+	+++	++ (bath height)	+++
FOV	+	+++	+	+++
Writing speed	+	+++	+	+++
Resin	hard/soft	hard/soft	soft	soft

Structuring Mode - Scanning Strategy

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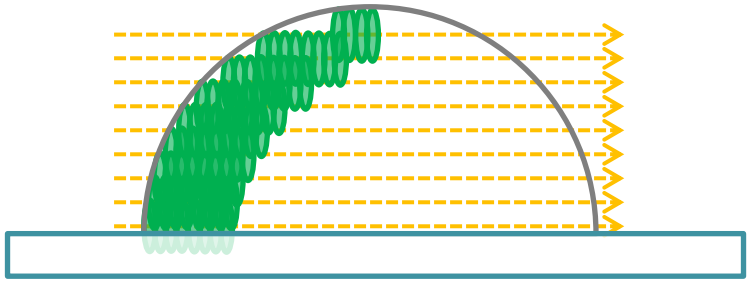
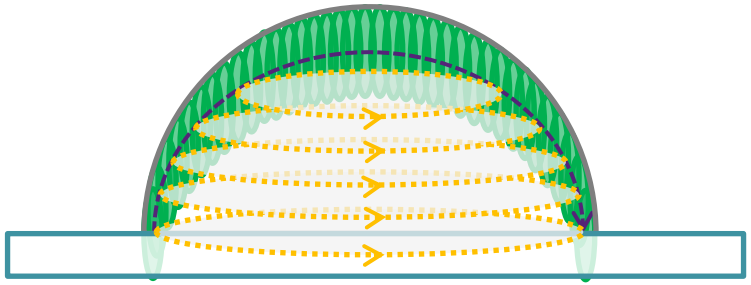
a company of Heidelberg Instruments

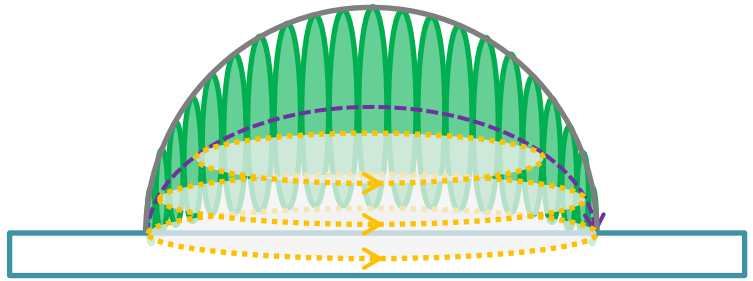
Conventional Two-Photon Polymerization (TPP)



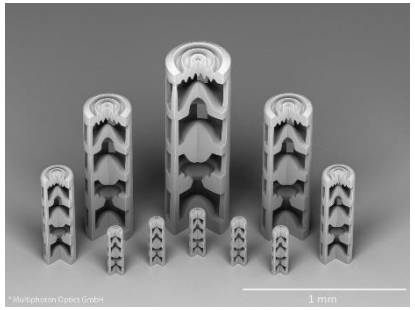
LCON3D: real 3D **L**aser **Con**touring

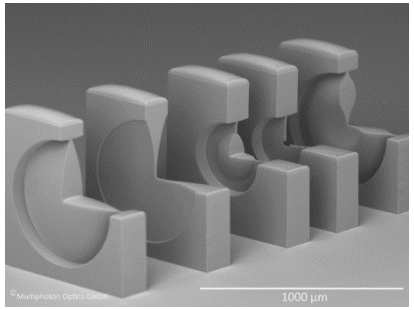


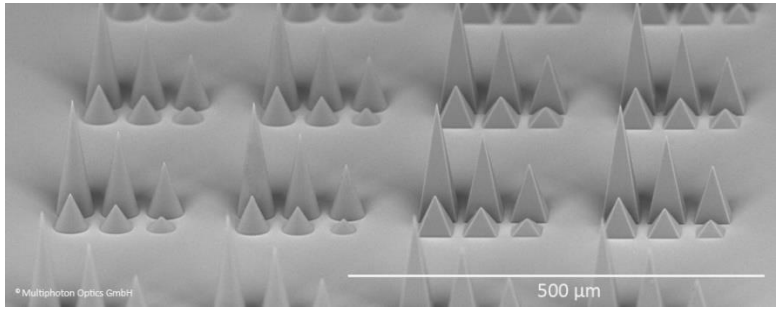
FALCON3D: real 3D **F**ast **A**daptive **L**aser **Con**touring

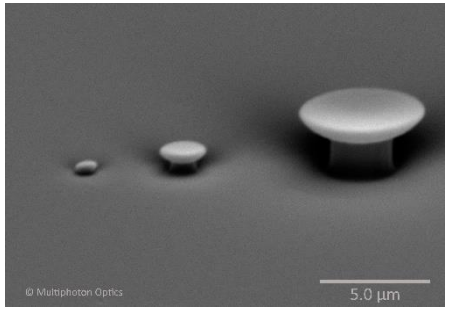


Examples of realized structures with conventional TPP

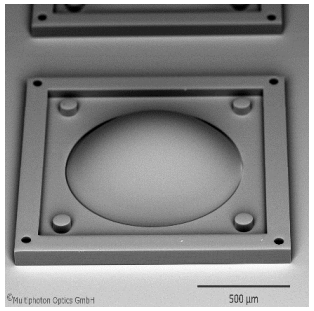


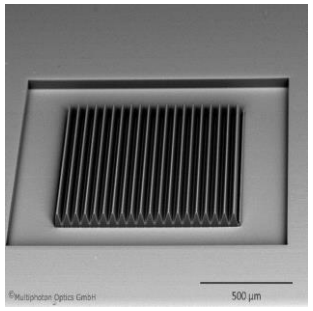


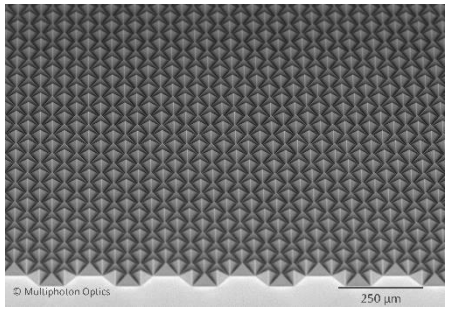


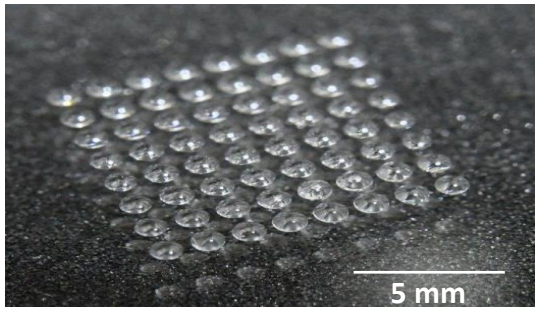


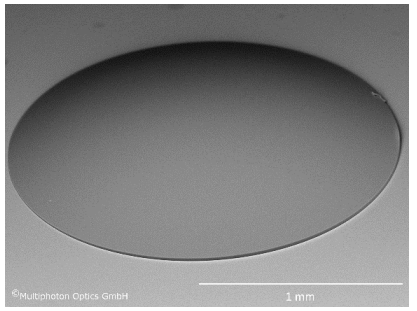
Examples of realized structures with LCON3D & FALCON3D

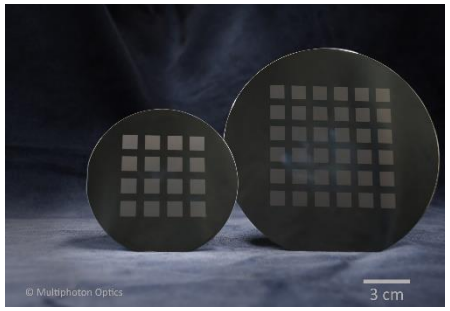












Component on Device: (3D) Endoscopy

Multiphoton Optics®
a company of Heidelberg Instruments

Challenge:

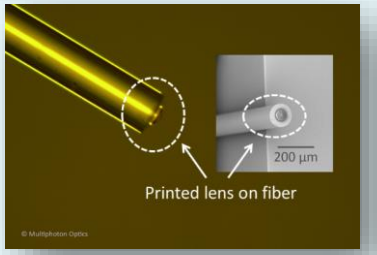
- Endoscopy enables the visualization of the inner body
- Current solutions exhibit large footprint or require expensive equipment with a complex setup

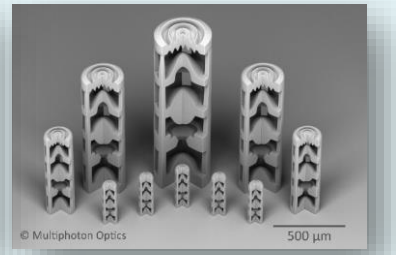
➔ **Examinations of blood vessels (Ø 0.5 mm) is hardly possible to detect plaques (stroke / heart attack)**

Endoscopy Solutions:

3D Printing of complex lens systems directly on the fiber tip

- Printing of lens systems in a single process step
- Freeform optic capability to enable large FoV
- Miniaturization to enable examination of smallest regions

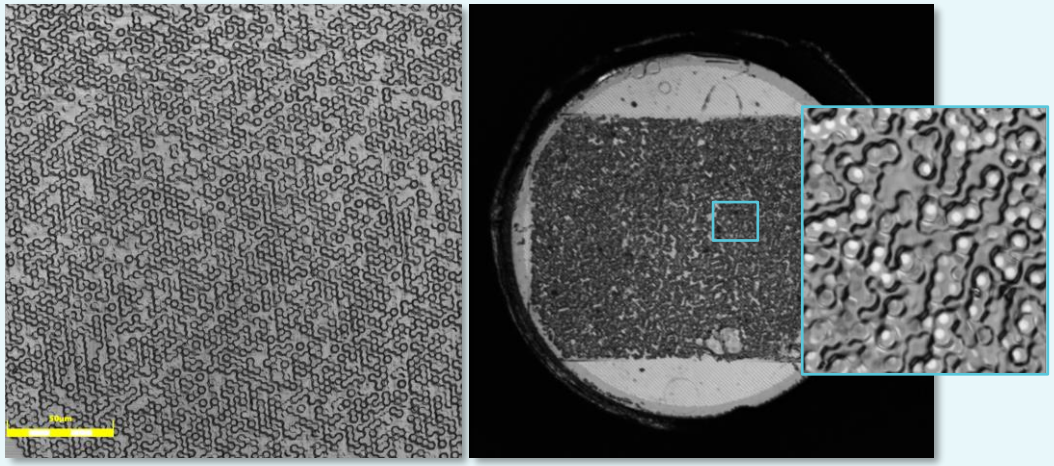




3D Endoscopy Solutions:

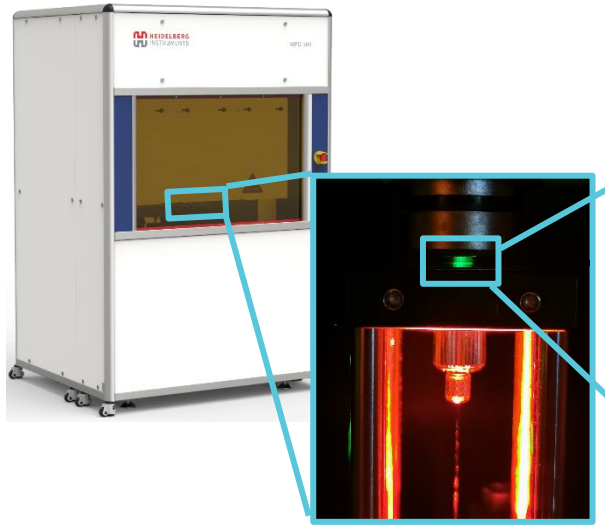
3D Printing of phase correcting optical elements on fiber tip overcomes SLM and large setup on fiber tip

- Printing of phase correcting optical elements on every core of the fiber with a great height accuracy
- Printing of individual structures for every fiber
- Miniaturization to enable examination of smallest regions

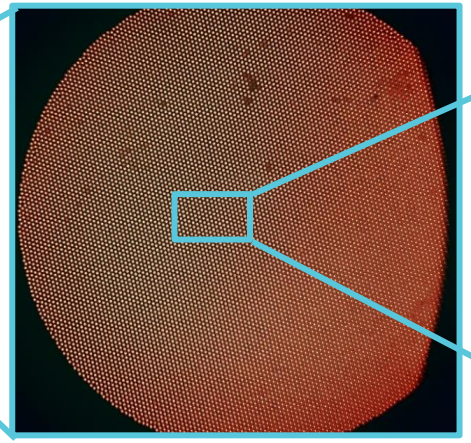


Fabrication Process – 3D Alignment

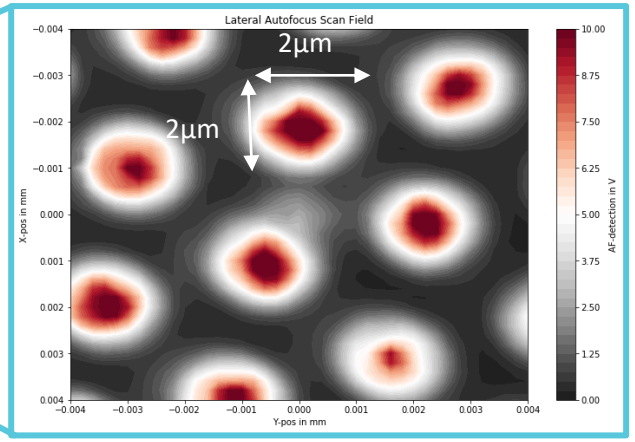
Multiphoton Optics®
a company of Heidelberg Instruments



Camera view



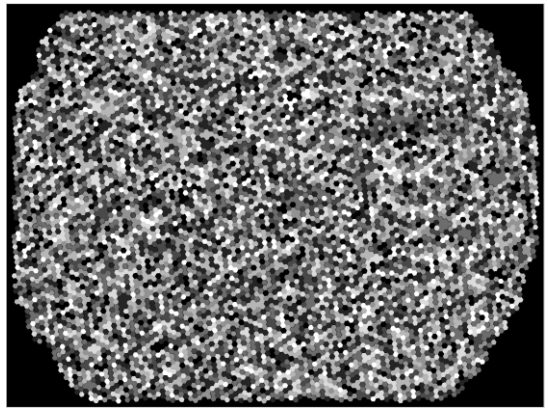
In situ confocal measurement



Fine alignment
(< 100 nm in XYZ)

3D Alignment
Rotation +
Triangulation

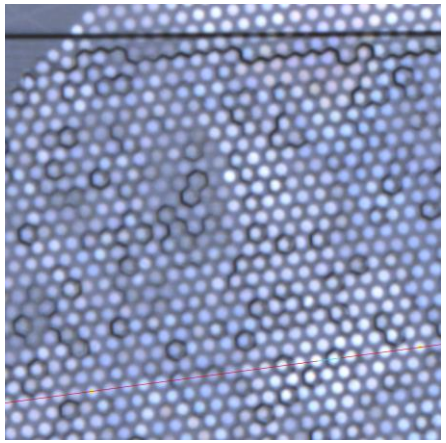
Input Design

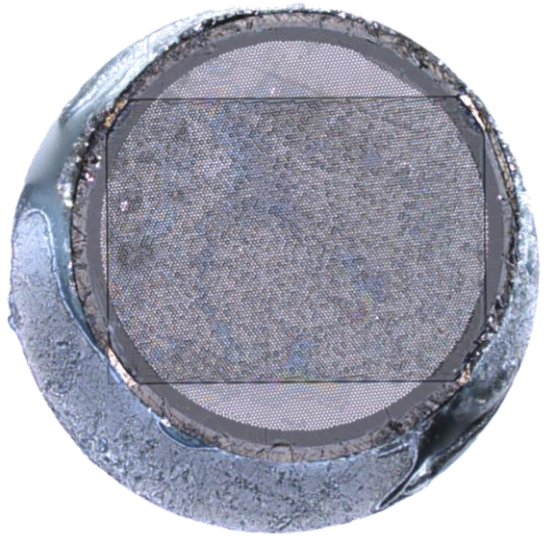


Writing

Development

Result





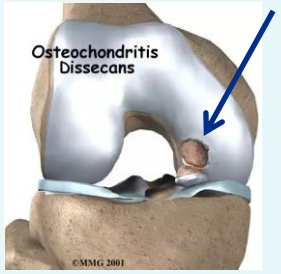
Biomedical Applications

Multiphoton Optics®
a company of Heidelberg Instruments

Challenge:

- **Bone cartilage defects** as a result of (sporting) accidents, arthrosis (caused by ageing), genetic defects
- **Low regenerative ability** of body for cartilage repairment
- Impairment of the **locomotor system**, **high costs** for public health care , …
- state-of-the-art therapies exhibit disadvantages

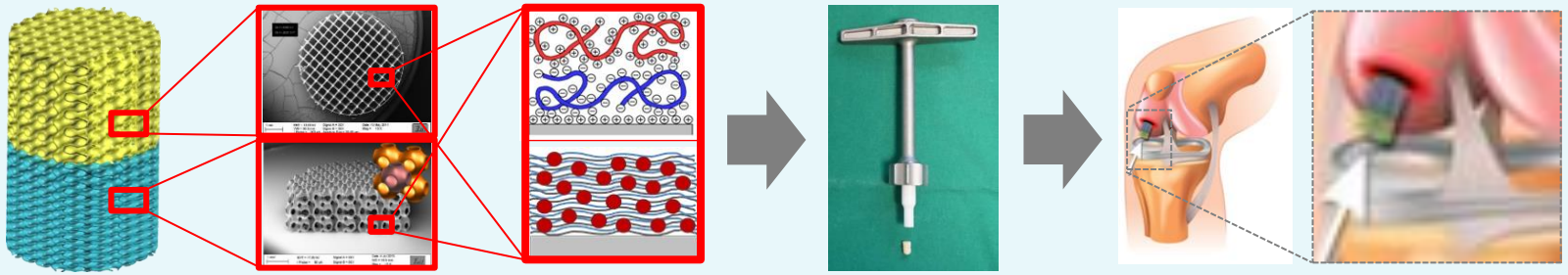
[1]



[2]

Solutions:

- **Artificial support structure** for tissue engineering
- **Biphasic** implants fostering regeneration of both **bone** and **cartilage** (cell differentiation)
- **Biodegradable** material

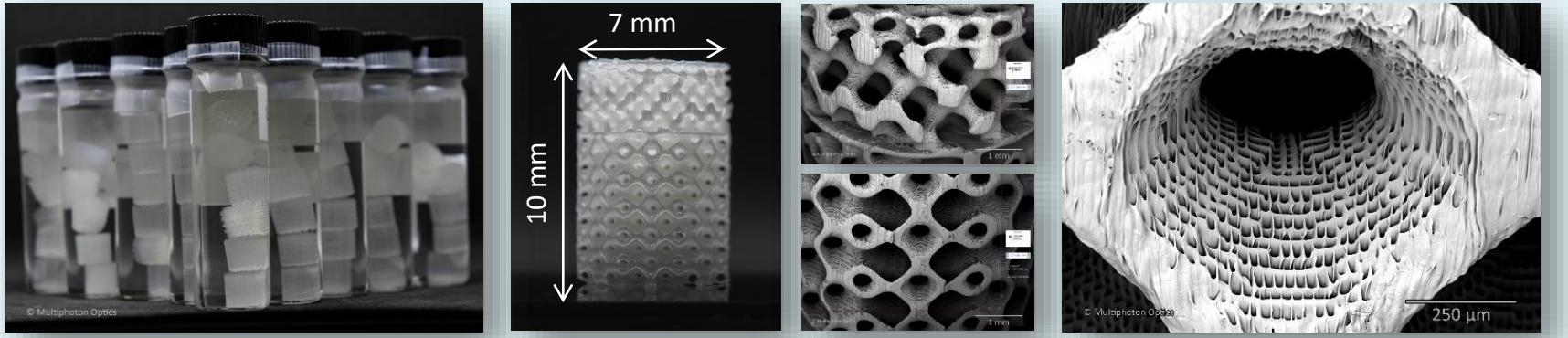


MPO Contribution:

Monolithic fabrication of biphasic scaffolds using biodegradable material

POLY-IMPLANT-DRUCK

SPONSORED BY THE
Federal Ministry of Education and Research



[1] Ghahremani et al., *Seminars in musculoskeletal radiology*, 18(5), 505-512. (2014), [2] http://www.advanceddynamic.com/article.php?aid=344

Photonic Applications – Examples with OrmoCore

Nanosystems and Technologies GmbH nanoplus

Multiphoton Optics®
a company of Heidelberg Instruments

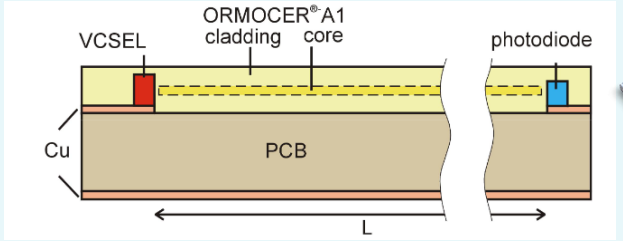
Challenge:

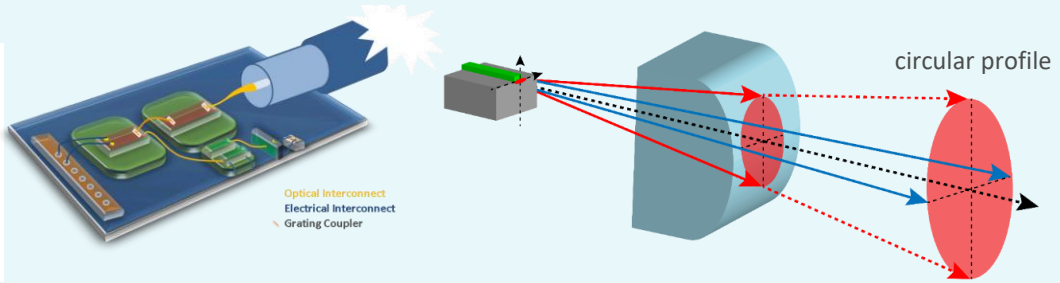
- Photonics packaging requires **accurate positioning** (< 0.5 µm) to avoid optical losses
- High positioning accuracy typically done by **active alignment**
- Active alignment **takes time** (minutes)
- **Investment** for assembly equipment is high

2D Process		3D Process
several process steps	**Waveguide fabrication**	only a few process steps
<< 1 µm	**Component positioning accuracy**	> 1 µm
active & time consuming	**Alignment**	passive

Solutions:

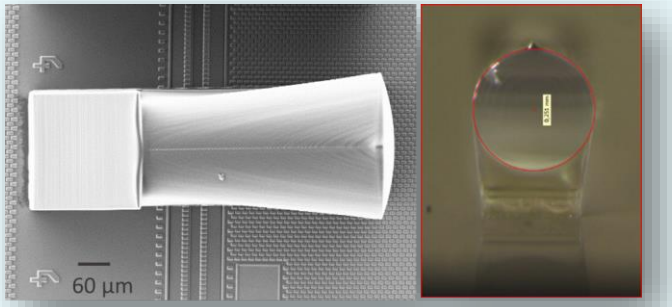
- Positioning of components first
- Relaxed positioning tolerance (> 1 µm) enables higher yield
- Fabrication of in-situ aligned waveguides



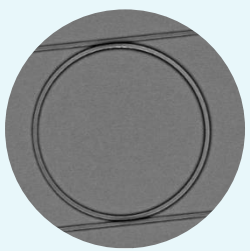


R. Houbertz et.al., Proc. MRS (2007); R. Houbertz et al., Proc. SPIE 7053, 70530B (2008),

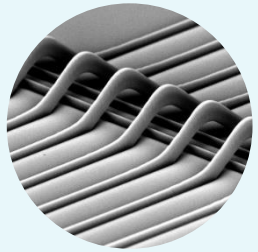
MPO Contribution:



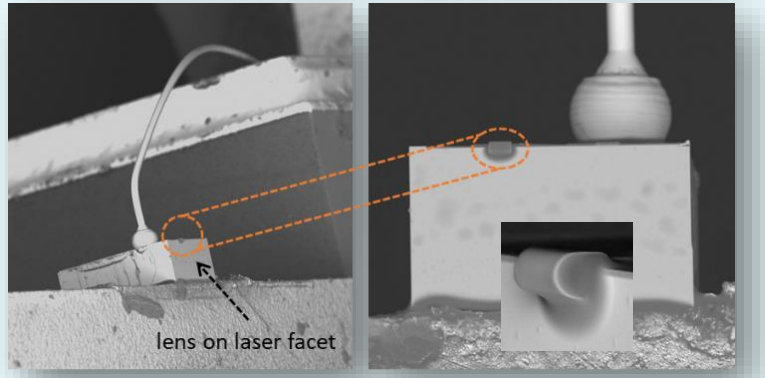
micro-collimator



ring resonator



3D waveguides



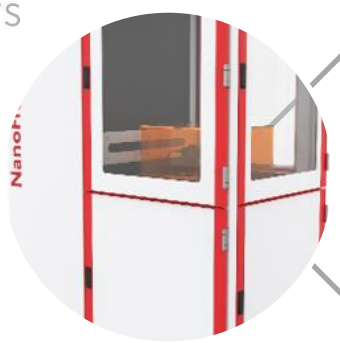
Heidelberg Instruments | Maskless Lithography for Nano- and Microfabrication

Multiphoton Optics®
a company of Heidelberg Instruments

Heidelberg Instruments Systems and Technology Pool

HEIDELBERG INSTRUMENTS

High-precision maskless aligner and laser lithography systems, for direct writing of 2D and 2.5D microstructures to mask-making.

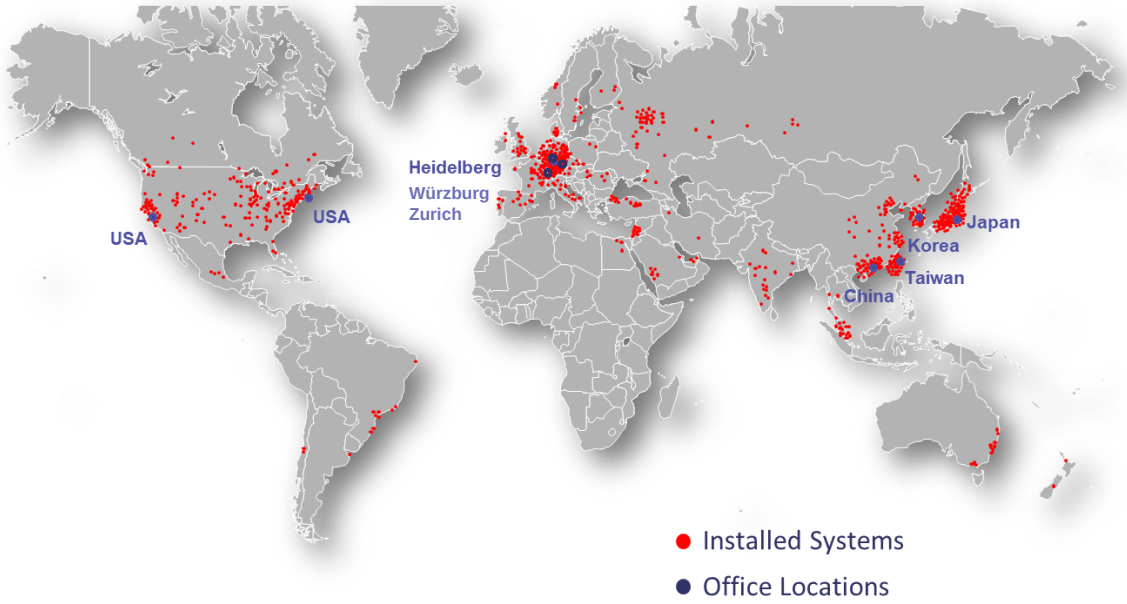


Thermal Scanning Probe Lithography (tSPL) for advanced nanofabrication.

Multiphoton Optics®

Maskless 3D Laser Lithography via Two-Photon Polymerization (TPP) for the fabrication of real 3D nano and microstructures.

Global Sales and Service Network



approx. **300 employees** – **7 countries** – **11 locations** –
global partner network on all continents –
more than **1,000 installed systems** in more than **50 countries**

Multiphoton Optics®

a company of Heidelberg Instruments

Thank you for joining!

For more information please visit our website multiphoton.de

or contact us via email

Jonas.Wiedenmann@multiphoton.de
Sales@multiphoton.de